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Optimization insulation thickness and reduction of CO_2 emissions for pipes in all generation district heating networks

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Abstract

District heating systems are provided solutions for the increasing energy problems in high-population cities. Energy costs go up depending on increasing heat loss in DHS's distribution network. Heat loss from the network consists of 5–20% of transferred energy, and this loss is higher than the other losses in the heating system. In the study, heat losses from the pipes such as supply-return pipes, hot water and circulation pipes into heat canals are investigated based on energy, exergy, economic and environmental. Optimum insulation thicknesses, energy savings, reduction of CO_2 emissions, the first investment costs and payback periods of the pipes in the network of all-generation district heating systems are investigated by using Life Cycle Cost Analysis (LCCA) method for fuel types like natural gas, fuel oil and coal. Optimum insulation thicknesses are calculated for different nominal sizes of pipes and various insulation materials such as glass wool, and rock wool for the different climatic zones. According to the results of the study, the heat losses from pipes in the 4th generation DHS network are decreased between 38.19% and 33.33% from the warmest climate zone to the coldest climate zone according to the 3rd generation. Energy savings, reduction of CO_2 emissions, payback periods and optimum insulation thickness values of supply and return pipes in the network are respectively changed between 7.80–98.86 \$/m, 39.61–322.32 kg CO_2/year, 0.028–0.38 years and 0.025–0.0105 m depending on various fuel types, insulation materials, nominal size pipes, climatic zones and all generation types.

Keywords

District heating network, LTDH network, reduction of CO_2 emisisons, life-cycle cost analysis (LCCA), optimum insulation thickness

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Introduction

Used to cover space heating and domestic hot water needs, district heating systems (DHS) transfer the heat produced in a plant to the buildings in a campus or region.[1] Components determined DHS are summarized as heat transfer fluid, heat transfer energy and energy sources used. In the systems low pressured vapour, hot water and superheated water are preferred as heat transfer fluids. Energy sources for the systems are arranged fossil fuels, nuclear power, waste heat, cogeneration heat, solar thermal energy, soil source heat pumps and biomass.[2] District heating systems, a century historical background, are separated into four generations depending on supply temperatures, fluid types and energy efficiency as shown Fig.1.[1] The systems are provided solutions for the increasing energy problems in high-population cities such as remediation of air quality because of reducing CO_2 emissions, increasing renewable energy sources share, and reducing energy export owing to control of energy demands.[3] The advantages of DHS can be sorted as high efficiency in heat production; fuel used diversity and low interaction with the environment.[4]

Shortly, the fall in energy consumption and heat demand in buildings is expected because of increasing energy efficiency precautions. The first investment cost, operation cost and total energy cost go up depending on increasing heat loss in DHS's distribution network. Thus there is a need decreasing of heat losses from pipes in the network. Heat loss from the network consists of 5–20% of transfer energy, and the loss is higher than the other losses in the heating system. Heat losses from the network depend on many factors such as outdoor conditions, insulation of pipes and length of the distribution network.[1–6] The installation of district heating (DH) systems constitutes an advantage in terms of total emission, and pollutant concentration (NOx, CO, PM). The authors presented that air quality is also improved and health externalities are reduced with the installation of a DH system compared to autonomous residential boilers in previous studies.[7] Because of the low operating temperatures, 4th generation district heating systems (low-temperature district heating systems), LTDH has an important potential in decreasing the heat losses from the networks. The decrease in the network's temperatures is caused positive effects in terms of energy efficiency. When the temperatures of the

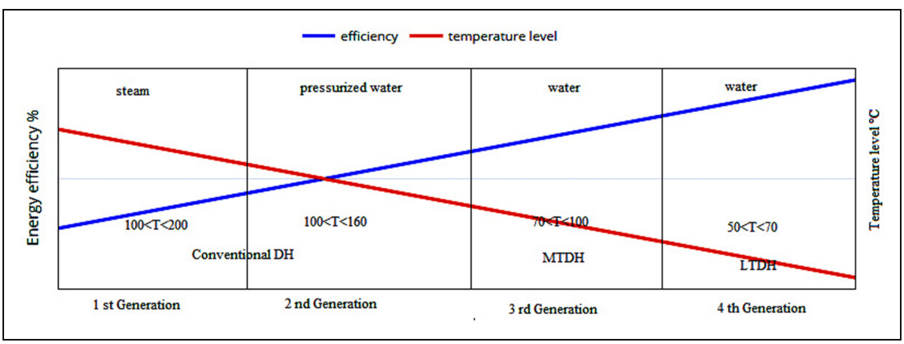

Figure 1. Classification of district heating system.

heat networks are decreased, the heat losses from the pipes in networks are reduced. This can create energy savings at a crucial amount. For example, in case the supply and return temperatures are reduced to 60°C/30°C from 80°C/40°C, the decrease in heat losses from the network is estimated at 30%. As heat sources such as geothermal energy, heat pumps and solar heating can be used in these systems, heat generation efficiency is increased.[8] Moreover, low heat losses are caused to lower temperature fluctuations and lower flow velocity is necessitated. For it causes a decrease in the pressure drop, pump energy demand falls.[6] But, though lower supply temperatures are enough to reach convenient room temperatures, these are the biggest problem in providing domestic hot water. Supply water temperature should be ensured that it does not fall under 60°C to prevent the reproduction and proliferation of legionella bacteria in the central domestic hot water systems.[9] This situation is caused to bigger energy consumption and higher heat losses from pipes in the distribution network in the demand the domestic hot water.[10]

Exergy is the maximum amount of work that can be done by the system depending on the ambient temperature. Exergy analysis is a method that can be used to increase energy production and conversion. Energy analysis allows for calculating the heat losses, but it does not provide the knowledge on how to convert energy. Because thermodynamics's second law determines that the part that can not be converted into useful work of all system's energy input, exergy analysis must be used with together energy analysis.[11] Exergy analysis is determined the losses and irreversibilities from the network and all system components in the district heating systems. The analysis presents the solutions to decrease irreversibility or exergy loss and to optimise the components and all system's performance depending on the type, location and size of the decrease in the work potential. In other words, the determination of where possible improvements in the system can be made is facilitated thanks to the exergy method as the locations and sizes of exergy losses are identified.[12–13]

Energy consumption for space heating can be decreased significantly by using suitable insulation material because of decreasing fossil fuel consumption and pollution effect on the environment. Even in well-insulated buildings energy consumption and emissions can be rather decreased by insulating heating pipes. Especially, district heating systems, industry and chemical proses plants have confused and expensive pipe configurations. Un-insulation supply and return pipes of the heating system are important sources of waste energy. Insulation application of pipe systems for energy savings not only decreases heat losses from the pipes but also reduces environmental pollution due to fuel savings. Thermal insulation material used is an effective method for thermal impact protection in the buildings and pipes. For this reason, the selection of suitable insulation material and determination of optimum insulation thickness is quite essential.[14–15] Suitable insulation usage on pipes network in the district heating system is one of the effective ways for energy savings. The insulation decreases fuel consumption and undesirable carbon emissions from fossil fuel combustion in the system.[16] The insulation material thickness must be preferred considering the thermal conductivity and cost of the insulation material with the average outdoor temperature of the region. The insulation thickness not only increases energy savings but also contributes to the decrease of environmental pollution. However, the insulation thickness supplied with no heat losses is neither practical nor economical. Thus, a balance point should be determined between the insulation material cost with energy savings obtained, and this point is shown as the optimum insulation thickness.[15–20]

Literature review

There are many studies related to distribution networks in the district heating system. Flores et al. [6] conducted a techno-economic comparison between networks with conventional DH and LTDH (100-40°C/43-60°). As the results of this study, decreasing the return water temperature is increased energy efficiency in LTDH systems, and pump power is decreased with lower energy demand and lower return water temperature. Furthermore, when the return water temperature falls by 10°C, heat losses of the distribution network are decreased by 6.7% and fell 23% of total pump energy. Gong and Werner [21] mapped flow diagrams of energy and exergy throughout the 2014 year of the district heating system in Sweden. Besides, they visualized the most efficient networks and investigated the use of renewable energy sources in district heating systems in Sweden. Li and Svendsen [13] analysed the energy and exergy of a hypothetical LTDH system's network (55/25°C) consisting of 30 buildings and compared the system's performance with MTDH systems (80/40°C). The total length of the network and annual heat demand are respectively calculated as 1.1 km and 187 kWh/m. Torio and Schmidt [22] investigated as a case study a small district heating system (95°C) in Kassel city in Germany. They presented the results of the energy and exergy analyses of the system. In the study, the strategies were derived for increasing the performance of the district heating systems based on the waste heat. According to the results of the study, in case the supply temperature of the system falls from 95°C to 57.7°C, the exergy efficiency of the system is raised from %32% to %39.3. Yang and Svendsen [23] analysed to determine the performance of an ultra low-temperature district heating system (ULTDH) in Denmark in terms of energy, exergy and economics based on data taken from the system in the study. The performance of the system was compared with medium and low-temperature district heating systems. According to the results of the analysis, low-temperature district heating systems (LTDH) have the highest energy and exergy efficiency. Ultra low-temperature district heating system (ULTDH) shows better performance in terms of energy, exergy and economics because of lower heat loss from the networks according to medium low-temperature district heating systems (MTDH). Baldvinsson and Nakata [24] investigated the energy and exergy performance of the low-temperature district heating system (60/30°C) located in Tohoku in North Japan. They concluded the low-temperature district heating system was not suitable for non-residential buildings in high places in North Japan. Comakli et al. [25] investigated the energy and exergy losses of heat distribution networks consisting of 11988 m length and 65–250 mm nominal size pipes of Ataturk University. The heat loss of the district heating network pipes was found as 8.62%. As a result of the study, the insulation material thickness is the most effective factor because of decreasing heat losses from the pipes. In case the insulation thickness of 20 cm uses instead of 8 cm on the pipes, the heat losses from the pipes are decreased by 25%. Keçebaş et al. [17] calculated the optimum insulation thickness, energy savings and payback periods of pipes used district heating network existed Afyonkarahisar Province in Turkey for five different nominal sizes of pipes and four fuel types during 10 years of economic life. In the study, an optimum model was developed based on Life Cycle Cost Analysis by (P_1-P_2) method. Rockwool was considered an insulation material and the network consisted of a network of 50–200 mm nominal size pipes. According to the results of the study, the optimum insulation thickness, energy savings and payback period were shown a change respectively between 0.085–0.228 m, 10.041 \$/m-175.171 \$/m and 0.442–0.808 years depending on different fuel types and pipe diameters. Rosti et al. [26] developed a methodology related to the determination of optimum insulation thickness by first investment cost of insulation and payback period for all climatic zones in Iran because of its economic and ecological importance. In the study, the optimization was carried out by using the Life Cycle Cost Analysis method with a numeric solution. Kayfeci [16] determined that significant energy savings can be obtained by insulating pipe networks and the great number of heat losses stem from the network of heat losses in the district heating system. In the study, the optimum insulation thickness, energy savings, annual operation cost and payback period were calculated by using the Life Cycle Cost Analysis method for different nominal pipe sizes, various insulation materials and heating degree days (HDD). The five different insulation materials were selected as XPS, EPS, foamboard, fibreglass and rock wool and natural gas was used as fuel. In the result of the study, the optimum insulation thickness was shown a change between 0.048–0.134 m; while energy-saving and payback periods were found respectively between 10.84 \$/m-49.78 \$/m and 0.74–1.29 years, and the best selection of insulation material was concluded to be fibreglass. Zhang et al. [20] calculated the optimum insulation thickness, energy savings and payback period of direct-buried pipes using a district heating network for various pipe diameters, fuel types and different soil deepness for Xion Province in China by using the Life Cycle Cost Analysis method in this study. According to the results of the study, the optimum insulation thickness, energy savings and payback period were respectively changed between 0.060–0.121 m, 36.395 \$/m-194.682 \$/m and 0.445–1.691 years.

In this study, energy and exergy are analysed the networks of all generations of district heating systems. The pipes such as supply-return pipes, hot water and circulation pipes into the network such as supply-return pipes, hot water and circulation pipes are investigated based on energy, exergy, economic and environmental. Energy and exergy losses from the pipes in the networks are modelled depending on the soil's deepness. The LTDH system is analysed compared to the other generations in terms of energy and exergy efficiency as a case study. Furthermore, the optimum analysis is included for the pipes in networks to obtain fuel savings and decrease energy and exergy losses. Optimum insulation thicknesses, energy savings, reduction of CO_2 emissions, first investment costs and payback periods of the pipes in the network of all generation district heating systems are investigated by using the Life Cycle Cost Analysis method for fuel types like natural gas, fuel oil and coal. Optimum insulation thicknesses are calculated for different nominal sizes of pipes (Ø20mm-Ø150 mm) and various insulation materials such as glass wool, and rock wool for the different climatic zones.

The novelty of this study mainly includes the following points:

- All generation district heating networks have been investigated based on energy, exergy and economics.
- Energy and exergy losses from the pipes in the networks are modelled depending on the soil's deepness. In the literature, many studies related to the optimum insulation thickness developed a methodology for heat losses from a pipe surrounded by outside air. Besides, optimum insulation thickness has been examined in all climatic zones big range of the heating degrees days.
- An LTDH system has been analysed as a case study and compared to the other generations.

Methodology

Heat losses from the pipes in the network

In the district heating system, the heat generated in the boilers is transferred by using hot fluid through a closed-loop network to the buildings on the campus. Space heating and domestic hot water demands of the buildings are covered with the heat transferred. In such a system, hot fluid is pumped inside the pipes at a constant low velocity under steady-state flow through networks to the buildings. Therefore, the pipes should be first handled as the major source of heat losses. Temperature changes in pipes from hot fluid to the surrounding environment (soil for buried pipes) are primarily effective in the assessment of insulation material and heat losses from pipes. Pressure drops and molecular diffusion are neglected in the study. To calculate heat losses from the pipes in the canals under soil per unit length, a resistance model is used shown in Fig.2.

Insulation material resistance;

$$R_i = \frac{1}{2 \times \pi \times k_i} \times In\left(\frac{r_2}{r_1}\right) \tag{1}$$

Canal resistance;

$$r_c = \frac{x_{cp}}{2 \times \pi} \tag{2}$$

$$R_c = \frac{1}{2 \times \pi \times k_c} \times In\left(\frac{r_{c+}t_c}{t_c}\right) \tag{3}$$

The convection resistance of the air in the canal;

$$R_{as} = \frac{1}{2 \times \pi \times h_{a \times} r_i} \tag{4}$$

The air convection coefficient can be found by the following formula.[27]

$$h_a = \frac{k_a}{D} \times Nu_D \tag{5}$$

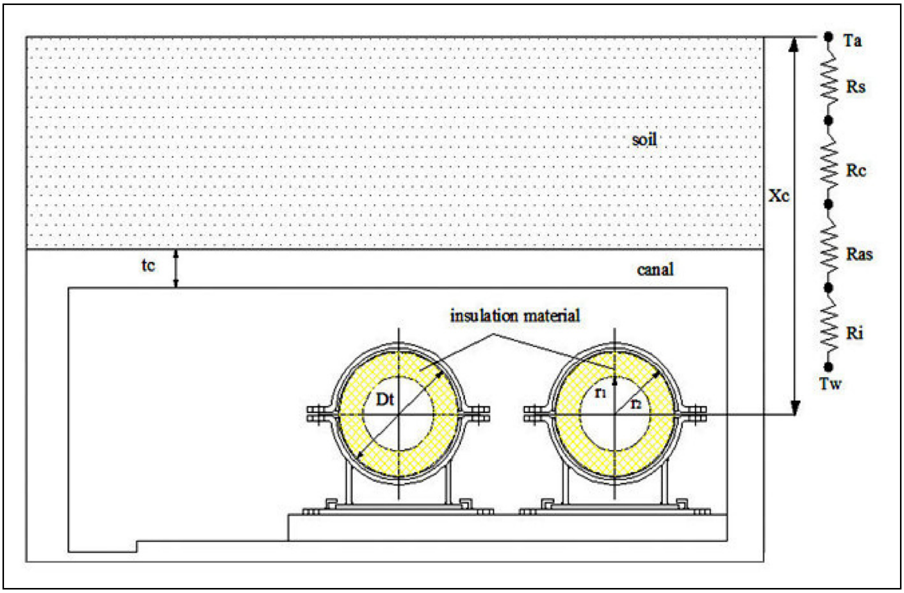

Figure 2. A sectional view of the canal and the resistance model.

To calculate the local Nusselt number at constant temperature and around a cylinder was proposed by Churchill the following formula.[28]

$$Nu_D = \left[0.6 + \frac{0.387 \times Ra_D^{1/6}}{[(1 + (0.559/Pr^{9/16}))]^{8/27}}\right]^2 \tag{6}$$

Soil resistance;

$$R_s = \frac{1}{2 \times \pi \times k_s} \times In\left[\frac{x_c}{r_c} \times \left(1 + \sqrt{1 - (D_t/x_c)^2}\right)\right] \tag{7}$$

Heat losses from the pipes in the canals per unit length can be calculated in the following formula.[27]

$$\dot{Q}_{PIPES} = \left[\frac{T_w - T_a}{R_i + R_{as} + R_c + R_s}\right] \tag{8}$$

Heating Degree Day (HDD) is a unit for measuring how much of a 24-h period is cold and explain the severity of the cold at a given time (day, month, year) taking into account the outside environment and room temperature. If the average daily temperature is above 15°C, heating is unnecessary. The heating cost is directly proportional to the annual HDD.

Annual heat loss from the pipes using HDD term is also can be calculated as follows [29]:

$$\dot{Q}_{PIPES} = 86400 \times \left[\frac{HDD}{R_i + R_{as} + R_c + R_s}\right] \tag{9}$$

Exergy analysis of the network

The exergy balance equation of the district heating system's all components is given with the following formula. The flow diagram related to the system is shown in Fig. 2.

$$\begin{aligned}\dot{E}_{fuel} + \dot{E}_{air} + \dot{E}_{electric} &= (E_{supply} - \dot{E}_{return})_{water} \\ &+ (\dot{E}_{fg} + \dot{E}_{surface} + \dot{E}_{pumps} + \dot{E}_{buildings} + \dot{E}_{pipes})_{loss} + \sum I_T\end{aligned} \tag{10}$$

Exergy loss from pipes in the canals and pumps can be calculated in the following formulas [27] (Figure 3).

$$\dot{E}_{pipes} = \dot{Q}_{pipes} \times \left(1 - \frac{T_a}{T_w}\right) \tag{11}$$

$$\dot{E}_{pumps} = \dot{W}_{pumps} \times \left(\frac{T_a}{T_w}\right) \tag{12}$$

Electric exergy input to the system is equal to the electric energy used to work the pumps.

$$\dot{E}_{electric} = \dot{W}_{pumps} \tag{13}$$

Optimization of pipes in the network

There are many methods of economic analysis to assess whether an investment is economical. In this study, the Life Cycle Cost Analysis and P_1-P_2 method, which is one of the economic analysis methods, was preferred for calculating the optimum insulation thickness. The life cycle cost analysis, which is used to estimate the total cost of the

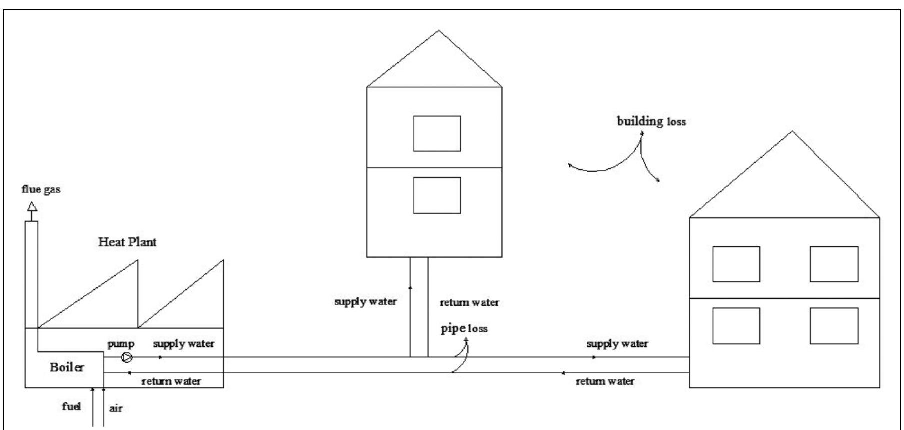

Figure 3. The schematic presentation of the flows in the district heating system.

project, includes the initial investment cost of the project, operating expenses, maintenance-repair cost and recycling costs. In other words, it covers a long period from the beginning of the project to the end of the usage period. In addition, the periodic maintenance costs of the investment are calculated. In P_1-P_2 method, economic analysis is carried out by taking into account the economic parameters such as interest and inflation rates, and fuel and insulation material prices. P_1 is the present value factor, which considers the impact of interest rates and inflation rates on the cost of heat loss in the future life cycle. P_2 considers the additional investment costs during the life cycle, including pipeline maintenance and resale at the end of the life cycle.[30]

Annual fuel consumption corresponding to heat losses from the pipes,

$$\dot{V}_{pl} = \frac{\dot{V}_f \times \dot{Q}_{PIPES}}{\dot{Q}_f \times \eta_s} \tag{14}$$

annual total fuel energy consumed by the heating system,

$$\dot{Q}_f = \overset{\dot{x}}{V}_f xH_u \tag{15}$$

and annual fuel consumption cost corresponding to heat losses from the pipes can be calculated with these formulas.

$$C_{fl} = \overset{\dot{x}}{V}_{pl} xC_f \tag{16}$$

The volume and cost of insulation material,

$$V_i = \pi \times (r_2^2 - r_1^2) \times L \tag{17}$$

$$C_{ins} = \mathrm{V}_i xC_i \tag{18}$$

energy savings can be calculated as follows:

$$\dot{Q}_{es} = \dot{Q}_{un-ins} - \dot{Q}_{ins} = \left[\left(\frac{1}{R_a + R_c + R_s} \right) - \left(\frac{1}{R_i + R_a + R_c + R_s} \right) \right] \times (T_w - T_a) \tag{19}$$

To determine the optimum insulation thickness, a lifetime cost analysis is required. While calculating the total cost, the lifetime (N) and the current value factor (P_1) are evaluated together. The current value factor varies depending on the interest rate (i), inflation rate (d) and the lifetime of the insulation (N). The net energy saving amount with insulation is obtained by using the P_1-P_2 method. The present value factor is calculated from the following equations, depending on whether the interest and inflation rates are equal.[14–17]

$$P_1 = \frac{1}{(d-i)} \times \left[1 - \left(\frac{1+i}{1+d} \right)^N \right] \quad if \quad i \neq d \tag{20}$$

$$P_1 = \frac{N}{(1+i)} \quad if \quad i = d \tag{21}$$

$$P_2 = 1 + P_1 \times C_m - \frac{r_v}{(1+d)^N} \tag{22}$$

P_2 can be taken as 1 if the maintenance and operation cost is zero. The total cost and annual net energy savings can be calculated by using the following formulas.[26–30]

$$C_{tot} = P_1 \times C_{fl} + \mathrm{P}_2 x C_{ins} \tag{23}$$

$$E_s = P_1 \times \dot{C}_f - P_2 \times C_{ins} \tag{24}$$

where C_f'is the difference between the energy cost for the uninsulated and insulated pipes. The payback period can be evaluated as the self-compensation process of the effect of insulation thickness cost on energy savings. The payback period of the insulation material varies depending on the properties such as the insulation material, the type of fuel and the annual interest rate. The payback period can be calculated for the situations i = d or i≠d and $P_2 = 1$ inserted to Eq.24 and by set equal to zero the equation.[16,17,29]

Annual emission savings,

$$ES_{CO2} = (\dot{V}_{pl-unins} - \dot{V}_{pl-ins}) \times H_u \times EF \tag{25}$$

where EF is the emission factor of CO_2 and takes different values depending on the fuel types of the heating system.[31]

System description

Space heating and hot water need of buildings in the 18. The Regional Directorate of Highways's campus, located in Kars city of Turkey is satisfied by the 4th generation low-temperature heating system (LTDH). Kars is the coldest city, situated in the fourth climatic zone of Turkey. The annual fuel consumption of the district heating system is an average of 809,793.50 Nm^3. Supply and return water temperatures of the district heating network are varied between 60°C and 50°C. The heat distribution network's length is 1470 m, and the sizes of the nominal pipes in the canals are varied from Ø20 mm to Ø150 mm. The layout plan of the district heating network is given in Fig. 4. As seen in the figure, the heat provided by burning fuel in boilers in Heat Plant is transferred to the buildings on the campus by the network.

While the space heating demand of the buildings is covered by supply and return water pipes in the canals, domestic hot water demand is covered by hot water and circulation pipes in the canals or network. This LTDH system analysed is compared to the other generations in terms of energy and exergy efficiency as a case study.

To investigate of optimum insulation thicknesses of the pipes in the canals are based on Life Cycle Cost Analysis and the P_1-P_2 method. The optimum insulation thicknesses, payback periods and energy savings, and reduction of CO_2 emissions are calculated for the different nominal size pipes (Ø20mm-Ø150 mm), different climatic zones and fuel types like natural gas, fuel oil and coal, all generations of the district heating system's network, insulation materials such as glass wool and rock wool. In the optimum analysis calculations, MATLAB Optimization Toolbox is used.

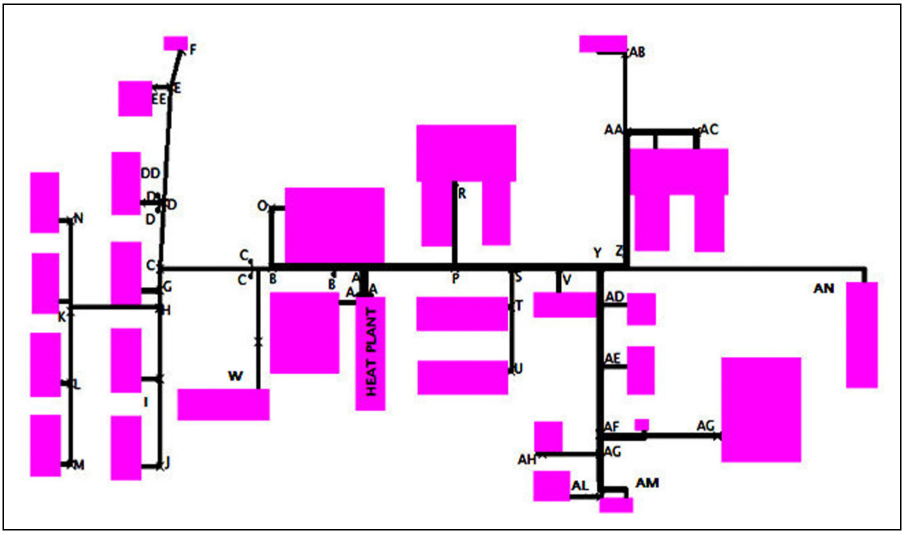

Figure 4. The location plan of the district heating network.

Results

Energy and exergy analysis of the LTDH network as a case study

In the district heating system's network, there are different diameters of heating pipes (supply and return pipes) between Ø25-Ø150 mm and the total length of 1760 m in the network consists of the canals. Besides while a total 1500 m length of hot water pipes has existed the different diameters of Ø25-Ø110 mm, there is a total 1498 m length of the circulation pipes (Ø20-Ø76 mm nominal size). Nominal sizes, insulation thicknesses and length of the pipes in the canals are shown in Table 1 at the current situation. The total length of the pipes in the canals is 4758 m, and the supply and return water temperatures of the network are varied between 60° and 50°C. At the under soil the deepness of the canal is average 1.2 m. In the system's network in four different sizes, the canals exist, and the values of the canal resistance are changed to 0.4403 from 0.3763.

Supply and return heating pipes, hot water pipes and circulation pipes in heat canals are insulated with glass wool to decrease heat losses. The thermal conductivity coefficient of insulation material is taken as k = 0.035 W/m.K, and soil resistance values are found between 1.3781–1.4130. Parameters and values used in resistance calculations are shown in Table 2.

Heat losses from all pipes in the district heating network are calculated as 50.41 kW, 33.68 kW of this loss stems from supply and return pipes and 16.72 kW of this loss from hot water and circulation pipes.

Considering all district heating systems annual heat loss value and heat loss ratio from all pipes in the network are found respectively as 1.57×10^9 kJ and 5.97%. Similarly,

Table 1. Annual heat and exergy losses of the pipes in the network.

	Pipe diameter mm	Insulation thickness mm	D_T mm	Pipes length m	Heat loss kJ/year	Exergy loss kJ/year
Supply and return pipes	150	60	270	240	1.74×10^8	1.59×10^8
	125	50	204	204	1.47×10^8	1.33×10^8
	100	50	140	140	9.11×10^7	8.30×10^7
	80	40	147	147	9.45×10^7	8.61×10^7
	65	40	249	249	1.46×10^8	1.33×10^8
	50	30	244	244	1.42×10^8	1.30×10^8
	40	30	86	86	4.55×10^7	4.15×10^7
	32	30	268	268	1.29×10^8	1.17×10^8
	25	30	119	119	5.17×10^7	4.71×10^7
	20	25	63	63	2.66×10^7	2.42×10^7
	Total			1760×2	1.05×10^9	9.54×10^8
Hot water pipes	110	50	210	380	7.75×10^7	6.67×10^7
	90	50	190	541	1.01×10^8	8.69×10^7
	76	40	156	60	1.13×10^7	9.75×10^6
	63	40	143	230	4.0×10^7	3.44×10^7
	50	30	110	48	8.41×10^6	7.23×10^6
	40	30	100	50	7.30×10^6	6.84×10^6
	32	30	92	18	2.38×10^6	2.24×10^6
	25	30	85	173	2.06×10^7	1.94×10^7
	Total			1500×1	2.50×10^8	2.33×10^8
Circulation pipes	76	40	156	452	8.54×10^7	7.34×10^7
	63	40	143	467	8.12×10^7	6.98×10^7
	50	30	110	60	1.05×10^7	9.04×10^6
	40	30	100	41	6.52×10^6	5.60×10^6
	32	30	92	237	3.43×10^7	2.94×10^7
	25	30	85	165	2.15×10^7	1.85×10^7
	20	25	70	76	9.64×10^6	8.28×10^6
	Total			1498×1	2.49×10^8	2.14×10^8

Table 2. Results of the resistant model.

Parameter	Value
Canal material	Concrete
k_c	2.1 W/m.K
R_c	0.376–0.441 W/m^2.K
t_c	20 cm
Insulation material	Glass wool
k_i	0.040 W/m.K
R_i	2.3387–4.985 W/m^2.K
Deepness of soil x_c	1.2 m
k_s	2 W/m.K
R_s	1.378–1.413 W/m.K
h_a	6.902–7.897 W/m^2.K
Ra_D	1.25×10^6-7.18×10^7
Nu_D	20.48–69.05

exergy loss from all pipes in the district heating network is calculated as 45.07 kW, and 30.68 kW of this loss stems from supply and return pipes and 7.50 kW of this loss from hot water and 6.88 of this loss from circulation pipes.

Considering all-district heating systems annual exergy loss value and exergy loss ratio from all pipes in the network are found respectively as 1.40×10^9 kJ and 4.90%. While 18 of the pumps with different sizes and capacities in the Heat Plant are used for space heating lines; 6 numbers of the pumps are used for hot water and circulation lines. The total power of the pumps is 3.37 kW and exergy loss from the pumps is 2.53 kW. Input exergy to the system is lost 0.27% from the pumps.

The supply and return water temperatures of the system were measured between 60°C and 50°C. Energy and exergy transferred to supply water from boilers are respectively figured out at 4292 kW and 157 kW. The exergy ratio transferred to supply water from the boilers is found as 17.07%.

Optimization of the pipes in the networks

To minimize the heat losses and fuel savings, the pipes should be investigated in terms of optimum insulation thickness. To calculate optimum insulation thicknesses, energy savings and payback periods of the pipes are used Life Cycle Cost Analysis and P_1-P_2 method.

Optimum insulation thicknesses are examined for different nominal sizes of pipes (Ø20mm-Ø150 mm) and various insulation materials such as glass wool, and rock wool for the different climatic zones and fuel types like natural gas, fuel oil and coal. Parameters and values used in the economic analysis are shown in Table 3.

Change of insulation, fuel and total annual costs according to insulation thickness is shown in Fig. 5 for 3rd generation, natural gas, Ø125 mm nominal size pipe and rock wool material. As seen in the figure while the insulation cost increases depending on the increase of the insulation thickness, the fuel cost decreases due to the reduction of heat losses thanks to the insulation. The total cost curve decreases up to one point depending on the insulation thickness and then starts to increase. The insulation thickness corresponding to this point indicates the optimum insulation thickness.

By the insulation application, heat losses from the pipes are reduced and fuel savings is provided. However, increasing the thickness of the insulation after the optimum insulation thickness not only increases the energy savings but also increases the cost of the insulation material.

In Fig. 6, the change in insulation thickness and annual energy savings are shown depending on the insulation material for the 4th generation, HDD = 4250 ° C days, Ø80 mm nominal size pipe, natural gas. As seen in the figure, while the energy savings changes increase at the first values of the insulation thickness, the energy savings changes decrease in the further values.

Rock wool insulation material provides higher energy savings compared to glass wool due to its low thermal conductivity coefficient. In the energy savings and insulation thickness figure, the insulation thickness corresponding to the highest energy savings value gives the optimum insulation thickness. In Fig. 7, annual energy savings is given with increasing insulation thickness depending on fuel types for 2nd generation, HDD = 3750 °C days, Ø125 mm nominal size pipe, rock wool material.

The highest energy saving is achieved in the fuel-oil fuel type and the lowest energy savings values are in the natural gas fuel type. Thermal insulation becomes more important in inefficient fuels such as fuel oil and coal than natural gas.

Annual energy savings values for supply and return pipes, hot water and circulation pipes are respectively changed between 7.80–98.86 $/m, 2.05–12.20 $/m depending on fuel types, generations of the district heating systems, insulation materials and climatic zones.

In Table 4, energy and emission savings and payback periods change ranges of the supply and return pipes are shown for the 4th generation according to the insulation materials and fuel types. The payback period that shows the value of energy savings achieved by applying insulation to the pipes in the heat network is equal to the initial investment cost and varies according to many variables such as fuel type, climate zone, generation of

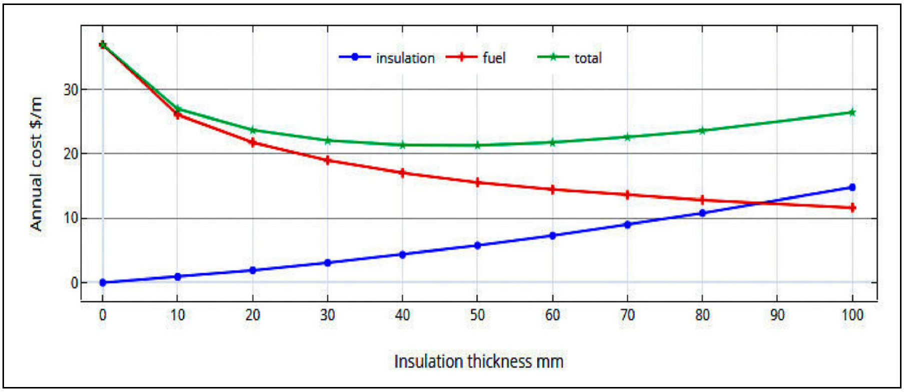

Figure 5. Change of annual costs with different insulation thicknesses (3rd generation, natural gas, Ø125 mm nominal size pipe, rock wool material).

Table 3. Parameters used in the economic and environmental analysis.[13–18,28]

Parameters	Values			
Heating degree-days (HDD)	1250–4250 °C days			
Insulation material	Glass wool		Rock wool	
Price, C_i	75 $/m^3		95 $/m^3	
k_i	0.040 W/m^2.K		0.035 W/m^2.K	
Fuel	Natural gas		Coal	Fuel-oil
Price, C_f	0.5022 $/m^3		0.3929 $/m^3	1.3202 $/m^3
H_u	8250 kcal/m^3		7007 kcal/kg	9875 kcal/kg
Emission factor of CO_2	0.234 kg CO_2/kWh		0.433 kg CO_2/kWh	0.330 kg CO_2/kWh
Efficiency of heating system	93%		65%	80%
Generations of DHS	1st generation	2nd generation	3rd generation	4th generation
Mean temperature of supply and return waters	125°C	110°C	80°C	55°C
Interest rate, i			10%	
Inflation rate, d			11%	
Lifetime, N			10 years	

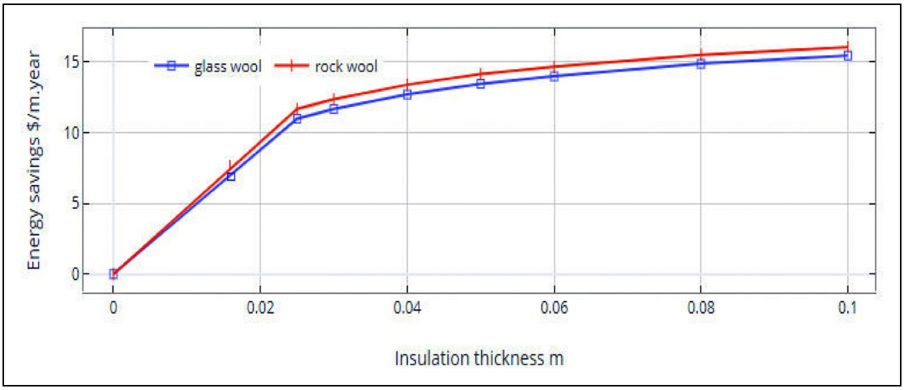

Figure 6. Change of energy savings with different insulation thicknesses for insulation materials (4th generation, HDD = 4250 °C days, Ø80 mm nominal size pipe, natural gas).

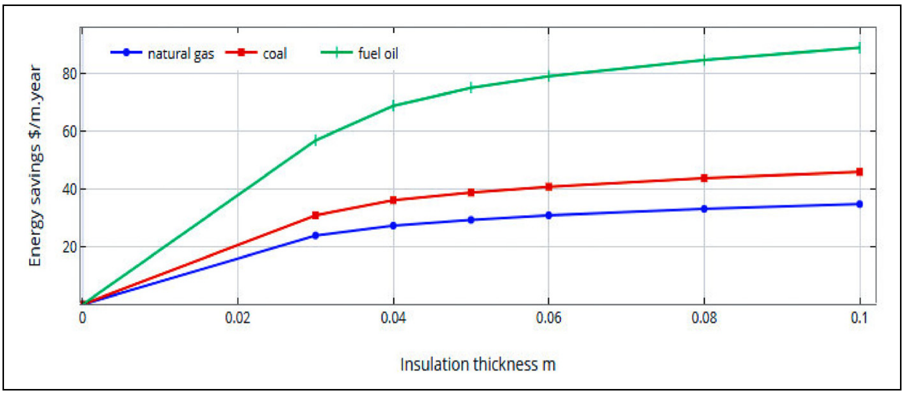

Figure 7. Change of energy savings with different insulation thickness for fuel types (2nd generation, HDD = 3750 °C days, Ø125 mm nominal size pipe, rock wool material).

district heating system and insulation material. Emission reduction of CO_2 has twice the value for the coal-fired heating systems compared to the other fuels because of maximum fuel savings. In Fig. 8, the payback period is shown depending on the insulation thickness and fuel types for the 3rd generation, HDD = 2250°C days, Ø100 mm nominal size pipe, glass wool material. While the highest payback period is found in natural gas heating systems, the lowest payback period is obtained from coal-fired heating systems.

In Fig. 9, the payback period is given depending on the insulation thickness and the type of insulation material for the 4th generation, HDD = 4250°C days, Ø80 mm of nominal size pipe, natural gas. Although glass wool insulation material provides lower energy savings than rock wool, it is lower than rock wool in terms of payback period due to its lower cost As can be seen from the figure, the payback period is increased

Table 4. Optimum insulation thickness, energy and emission savings, payback periods change ranges of the supply and return pipes depending on the insulation materials and fuel types.

		Supply and return pipes			
		4th generation, HDD = 2750 °C days			
		Optimum thickness m	Energy savings $/m.year	Emission reduction kg CO_2/year	Payback period years
Nominal size		RW-GW	RW-GW	RW-GW	RW-GW
Ø125	Natural gas	0.035-0.040	12.55-12.64	63.73-64.16	0.28-0.31
	Fuel oil	0.061-0.069	34.98-34.60	114.07-110.47	0.21-0.20
	Coal	0.037-0.041	17.40-17.39	177.53-177.43	0.27-0.28
Ø100	Natural gas	0.034-0.040	12.48-11.88	63.35-60.32	0.25-0.24
	Fuel oil	0.061-0.068	34.61-33.16	112.85-108.27	0.17-0.18
	Coal	0.036-0.040	16.48-16.47	168.06-167.92	0.22-0.23
Ø80	Natural gas	0.034-0.039	12.14-11.52	61.66-58.48	0.22-0.19
	Fuel oil	0.060-0.066	33.96-32.42	110.70-108.12	0.15-0.14
	Coal	0.035-0.039	16.04-16.12	163.58-164.42	0.17-0.19
Ø65	Natural gas	0.033-0.037	11.49-11.42	58.37-58.02	0.20-0.17
	Fuel oil	0.060-0.063	33.96-32.56	110.70-106.16	0.13-0.12
	Coal	0.034-0.036	15.85-15.09	161.73-155.85	0.15-0.17
Ø50	Natural gas	0.030-0.035	10.46-10.82	53.11-54.96	0.18-0.17
	Fuel oil	0.056-0.061	32.55-33.22	106.12-105.93	0.13-0.11
	Coal	0.033-0.035	15.15-15.28	154.47-153.92	0.15-0.16
	Natural gas	0.028-0.033	9.92-10.34	50.37-52.48	0.15-0.14
Ø40	Fuel oil	0.053-0.056	31.77-30.09	103.58-98.10	0.10-0.09
	Coal	0.030-0.032	14.53-14.72	148.17-150.07	0.13-0.12
	Natural gas	0.025-0.030	9.38-9.84	47.68-49.98	0.12-0.10
Ø32	Fuel oil	0.050-0.053	30.75-29.03	100.29-94.65	0.08-0.07
	Coal	0.028-0.030	13.88-12.99	141.61-132.58	0.10-0.11

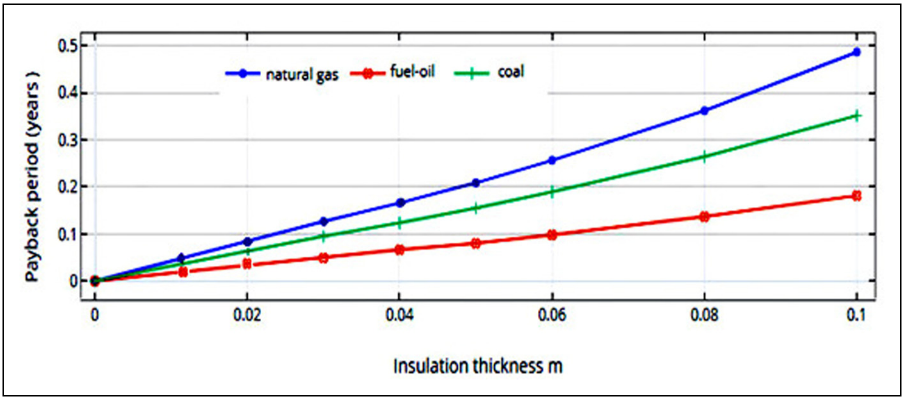

Figure 8. Effect of insulation thickness on the payback period for fuel types (3rd generation, HDD = 2250 °C days, Ø100 mm nominal size pipe, glass wool material).

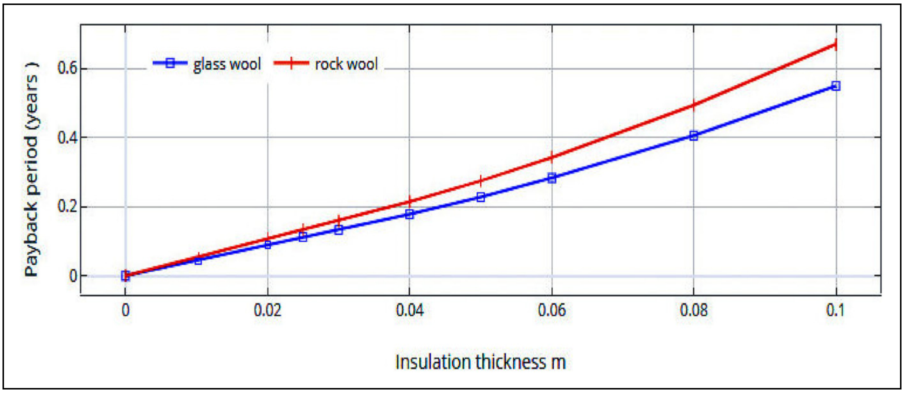

Figure 9. Effect of insulation thickness on the payback period for insulation material (4th generation, HDD = 4250°C days, Ø80 mm nominal size pipe, natural gas).

by increasing the insulation thickness. Payback period values for supply and return pipes, hot water and circulation pipes are respectively changed between 0.028–0.38 years, 0.063–0.47 years depending on fuel types, generations of the district heating systems, insulation materials and climatic zones.

Optimum insulation thicknesses, annual energy saving values, payback periods, annual fuel consumption values of the heating system pipes, hot water and circulation pipes of different diameters have been investigated depending on fuel type, climatic zones, insulation material and generation type of the district heating system.

In Fig. 10, optimum insulation thickness values of pipes of different diameters in the heating system are given for different insulation materials and different types of fuel for 3rd generation and HDD = 2750°C days. While optimum insulation thicknesses are the lowest in natural gas, it is the highest in fuel oil. Also, optimum insulation thicknesses are lower for rock wool insulation material than glass wool material.

Optimum insulation thickness values for supply and return pipes, hot water and circulation pipes are respectively changed between 0.025–0.105 m, 0.020–0.050 m depending on fuel types, generations of the district heating systems, different insulation materials and climatic zones.

Comparison of all generation networks

District heating systems, a century historical background, have been separated into four groups (generations) depending on supply temperatures, fluid types and energy efficiency. In this study, energy and exergy losses from the pipes in the district heating network and optimum thickness, energy savings and payback periods of the pipes are examined in terms of these four generations.

According to the results of the study energy and exergy losses from pipes in the district heating network rise with an increase in heating degree days (HDD) value. Depending on the supply and return water temperatures in the network, energy and exergy losses from pipes decrease to 4th generation from 1st generation district heating system. The heat losses from pipes in the 4th generation DHS network decreased between 38.19% and 33.33% from the warmest climate zone to the coldest climate zone according to the 3rd generation. In addition, the heat losses from pipes in the 4th generation DHS network decreased between 64.01% and 58.40% from the warmest climate zone to the coldest climate zone according to 1st generation.

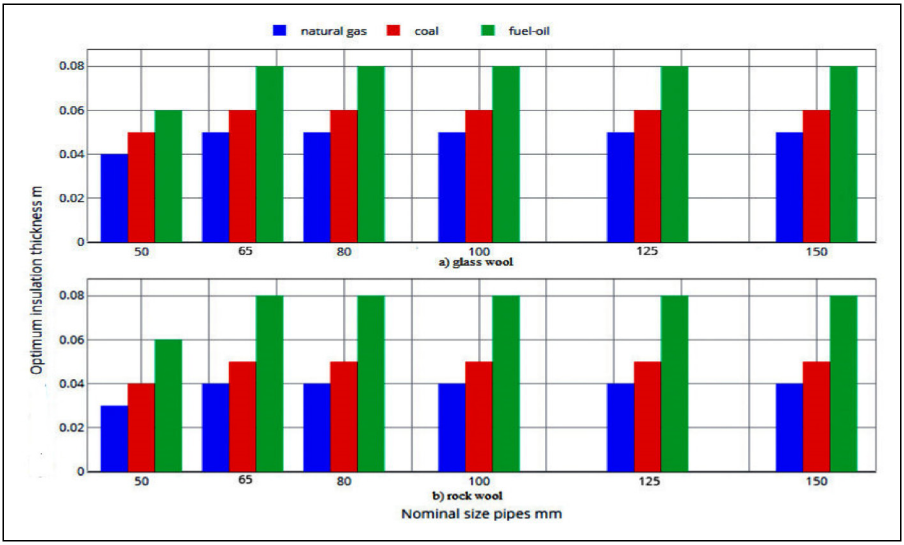

Figure 10. Optimum insulation thickness of the insulation material and fuel types for nominal size pipes (for 3rd generation and HDD = 2750°C days).

In Fig. 11, the change of the exergy factor is shown for 150 mm of nominal size pipe depending on the different climatic zones and generations. The exergy factor means the ratio of heat losses and exergy losses. As can be seen from the figure, the biggest change in the exergy factor is observed in the 4th generation DHS network. The highest exergy factor values for the constant HDD value are reached in the 1st generation.

Optimum insulation thickness values of supply and return pipes, hot water and circulation pipes in the network are investigated for all DHS generations, fuel types, different climatic zones and different diameters of pipes.

In Fig. 12, optimum insulation thicknesses of supply and return pipes by different nominal sizes in the network are shown depending on fuel and generation types for rock wool insulation material and HDD = 2750°C days. As seen in the figure, while the optimum insulation thickness value reaches the highest value in fuel oil, it is the lowest value in natural gas because of being the most efficient fuel type. For this reason, natural gas-fired district heating systems are cheaper than the other fuel types in terms of initial investment cost The new generation, 4th generation district heating systems, also have the lowest optimum insulation thickness values due to low network pipe temperatures. In Fig. 13, changes in energy savings are given related to insulation thickness and generation types for Ø80 mm pipe, glass wool material and HDD = 1250°C days. The highest energy savings values are found in fuel oil-fired systems and 1st generation. This result shows how important to insulate the pipes in the network of the existing traditional district heating systems at suitable insulation thicknesses. While annual energy savings, emission reduction of CO_2, payback periods and optimum insulation thickness values are respectively changed between 27.65–98.86 \$/m, 140.41–322.32 kg CO_2/year, 0.028-0.21 years and 0.040 –0.105 m for supply and return pipes in the 1st generation network from the warmest zone to the coldest climate zone; changes of these values are respectively changed for supply and return pipes in the 4th generation network are respectively observed between 7.80-34.80 \$/m, 39.61–113.44 kg CO_2/year, 0.066–0.38 years and 0.025–0.080 m depending on

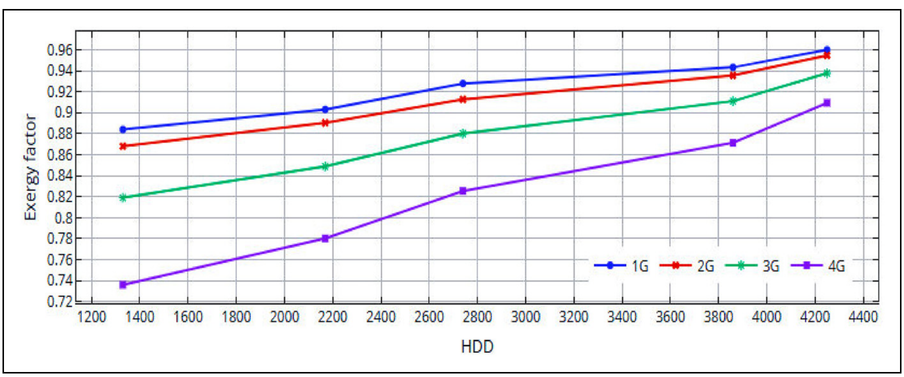

Figure 11. Exergy factor of the generation types for various HDD (for Ø150 mm pipe and glass wool material).

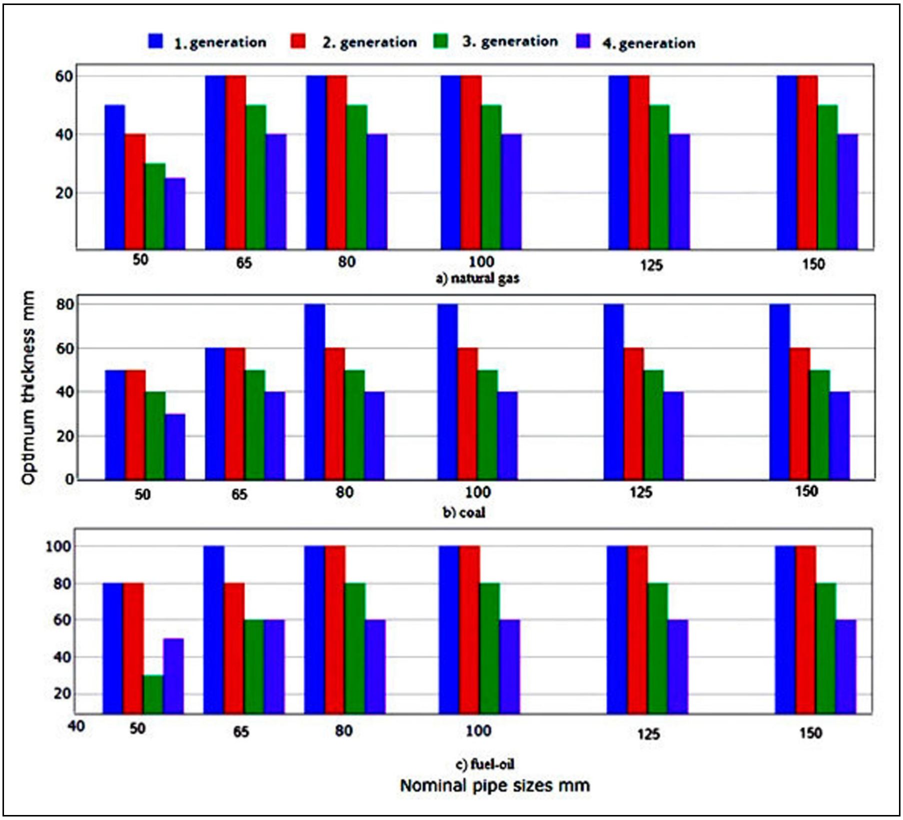

Figure 12. Optimum insulation thickness of the generation types for all fuel types (for rock wool material and HDD = 2750°C days).

various fuel types, insulation materials, nominal size pipes and climatic zones. Annual energy savings, emission reduction of CO_2, payback periods and optimum insulation thickness values of hot water and circulation pipes in the network are respectively calculated between 2.05–12.20 $/m, 10.43–39.79 kg CO_2/year, 0.063–0.47 years and 0.020–0.050 m. These values vary depending on the type of fuel, insulation material and various nominal size pipes, but not depending on the type of generation network. Optimum insulation thickness, energy savings and payback periods change ranges of the supply and return pipes (nominal size of Ø150 mm) for all generations are given in the Appendix tables.

Conclusions

In this study, energy and exergy losses from the pipes in the networks are modelled depending on the soil's deepness. The LTDH system is analysed compared to the

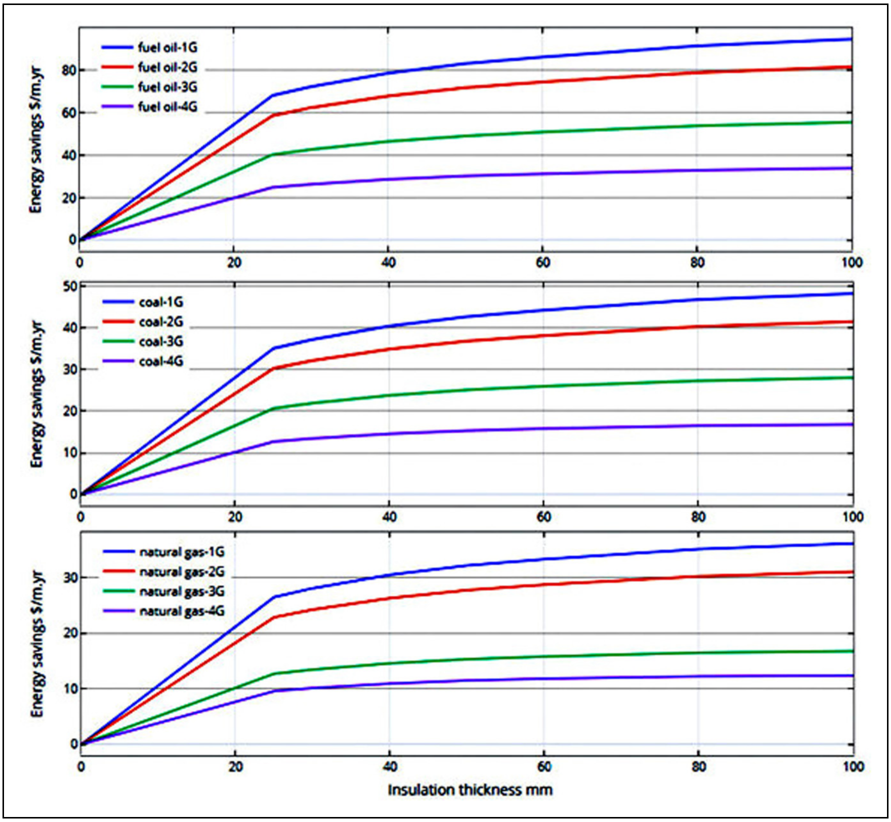

Figure 13. Change of energy savings related to insulation thickness (HDD = 1250°C days for Ø80 mm pipe and glass wool material).

other generations in terms of energy and exergy efficiency as a case study. Optimum insulation thicknesses, energy savings, reduction of CO_2 emissions, first investment costs and payback periods of the pipes in the network of all generation district heating systems are investigated by using the Life Cycle Cost Analysis method for fuel types like natural gas, fuel oil and coal various insulation materials such as glass wool, rock wool for the different climatic zones. Besides the results were obtained compatible and confirmed with the scientific studies presented in the reference part. Based on the analysis results the major conclusions can be drawn:

1. The highest energy saving is achieved in the fuel-oil fuel type and the lowest energy savings values are in the natural gas fuel type. Thermal insulation becomes more important in inefficient fuels such as fuel oil and coal than natural gas. While the highest payback period is found in natural gas heating systems, the lowest payback period is obtained from coal-fired heating systems.

Although glass wool insulation material provides lower energy savings than rock wool, it is lower than rock wool in terms of payback period due to its lower cost While optimum insulation thicknesses are the lowest in natural gas fuel, it is the highest in fuel oil fuel type. Also, optimum insulation thicknesses are lower for rock wool insulation material than glass wool material.

2. Depending on the supply and return water temperatures in the network, energy and exergy losses from pipes decrease to 4th generation from 1st generation district heating system. The heat losses from pipes in the 4th generation DHS network decreased between 38.19% and 33.33% from the warmest climate zone to the coldest climate zone according to the 3rd generation. Besides the heat losses from pipes in the 4th generation DHS network decreased between 64.01% and 58.40% from the warmest climate zone to the coldest climate zone according to 1st generation. The biggest change in exergy factor is observed in the 4th generation DHS network. The highest exergy factor values for the constant HDD value are reached in the 1st generation.
3. Optimum insulation thickness values for supply and return pipes, hot water and circulation pipes are respectively changed between 0.025–0.105 m, 0.020–0.050 m depending on fuel types, generations of the district heating systems, different insulation materials and climatic zones. While optimum insulation thickness value reaches the highest value in fuel oil, it is the lowest value in natural gas because of being the most efficient fuel type. For this reason, natural gas-fired district heating systems are cheaper than the other fuel types in terms of initial investment cost The new generation, 4th generation district heating systems, also have the lowest optimum insulation thickness values due to low network pipe temperatures.
4. Annual energy savings, payback periods and optimum insulation thickness values of supply and return pipes in the network are respectively changed between 7.80–98.86 $ / m, 0.028–0.38 and 0.025–0.0105 m depending on various fuel types, insulation materials, nominal size pipes, climatic zone. The highest energy savings values are found in fuel oil-fired systems and 1st generation. This result shows how important to insulate the pipes in the network of the existing traditional district heating systems at suitable insulation thickness and all generation types.
5. Finally, emission reduction of CO_2 has twice the value for the coal-fired heating systems compared to the other fuels because of maximum fuel savings.

Declaration of conflicting interests

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Appendix

Table A1. Optimum insulation thickness, energy savings and payback periods change ranges of the supply and return pipes (Ø150 mm) for 1st generation.

		Supply and return pipes (Ø150 mm)			
		1st generation			
		Optimum thickness m	Energy savings \$/m.year	Emission reduction kg CO_2/year	Payback period years
		RW-GW	RW-GW	RW-GW	RW-GW
HDD = 1250 °C days	Natural gas	0.052-0.054	29.29-27.65	148.73-410.41	0.26-0.21
	Fuel oil	0.092-0.095	85.34-81.35	278.22-265.23	0.17-0.14
	Coal	0.055-0.072	38.68-39.74	393.48-405.32	0.19-0.22
HDD = 2250 °C days	Natural gas	0.054-0.058	29.93-28.25	151.96-143.45	0.25-0.21
	Fuel oil	0.094-0.098	87.19-83.12	284.29-271.02	0.17-0.14
	Coal	0.055-0.074	39.52-40.60	403.13-414.13	0.19-0.21
HDD = 2750 °C days	Natural gas	0.056-0.060	30.59-28.88	155.34-146.62	0.25-0.21
	Fuel oil	0.96-0.100	89.12-84.96	290.55-277.01	0.17-0.14
	Coal	0.057-0.075	40.39-41.50	412.09-423.31	0.19-0.21
HDD = 3750 °C days	Natural gas	0.057-0.061	31.26-29.50	158.70-149.80	0.24-0.20
	Fuel oil	0.98-0.102	91.05-86.81	296.85-283.03	0.16-0.14
	Coal	0.059-0.078	41.27-42.40	421.02-432.45	0.18-0.20
HDD = 4250 °C days	Natural gas	0.060-0.063	31.81-30.03	161.53-152.46	0.24-0.20
	Fuel oil	0.100-0.105	92.68-98.86	302.13-322.32	0.16-0.13
	Coal	0.060-0.080	42.01-43.15	428.49-440.18	0.18-0.20

RW(Rock wool), GW(Glass wool).

Table A2. Optimum insulation thickness, energy savings and payback periods change ranges of the supply and return pipes (Ø150 mm) for 2nd generation.

		Supply and return pipes (Ø150 mm)			
		2nd generation			
		Optimum thickness m	Energy savings \$/m.year	Emission reduction kg CO_2/year	Payback period years
		RW-GW	RW-GW	RW-GW	RW-GW
HDD = 1250 °C days	Natural gas	0.046-0.054	23.91-23.89	121.40-121.33	0.25-0.24
	Fuel oil	0.080-0.094	70.01-70.31	228.25-229.23	0.16-0.16
	Coal	0.050-0.071	33.43-34.34	341.01-350.30	0.22-0.25
HDD = 2250 °C days	Natural gas	0.048-0.057	24.51-24.49	124.46-124.39	0.24-0.24
	Fuel oil	0.080-0.095	71.76-72.08	233.97-234.98	0.15-0.16
	Coal	0.051-0.074	34.27-35.21	349.57-359.08	0.22-0.25
HDD = 2750 °C days	Natural gas	0.050-0.060	25.14-25.12	127.61-127.57	0.24-0.24
	Fuel oil	0.085-0.097	73.60-73.92	239.95-241.01	0.15-0.16
	Coal	0.053-0.075	35.15-36.11	358.50-368.26	0.21-0.24
HDD = 3750 °C days	Natural gas	0.054-0.060	25.76-25.75	130.81-130.74	0.23-0.23
	Fuel oil	0.096-0.099	79.47-75.76	259.09-247.04	0.14-0.15
	Coal	0.055-0.077	36.02-37.00	367.43-377.44	0.21-0.23
HDD = 4250 °C days	Natural gas	0.055-0.060	26.28-26.27	133.48-133.41	0.23-0.22
	Fuel oil	0.098-0.100	81.09-77.31	264.37-252.04	0.18-0.15
	Coal	0.057-0.078	36.75-37.76	374.93-385.17	0.20-0.23

Table A3. Optimum insulation thickness, energy savings and payback periods change ranges of the supply and return pipes (Ø150 mm) for 3rd generation.

		Supply and return pipes (Ø150 mm)			
		3rd generation			
		Optimum thickness m	Energy savings \$/m.year	Emission reduction kg CO_2/year	Payback period years
		RW-GW	RW-GW	RW-GW	RW-GW
HDD = 1250 °C days	Natural gas	0.042-0.051	15.17-15.42	77.01-78.31	0.30-0.31
	Fuel oil	0.079-0.080	48.02-45.58	156.56-148.62	0.23-0.19
	Coal	0.045-0.053	21.65-21.64	220.89-220.75	0.27-0.27
HDD = 2250 °C days	Natural gas	0.041-0.050	15.73-15.52	79.84-81.18	0.29-0.30
	Fuel oil	0.080-0.080	49.78-47.26	162.28-154.84	0.22-0.18
	Coal	0.045-0.055	22.45-22.44	228.98-228.83	0.27-0.26
HDD = 2750 °C days	Natural gas	0.042-0.053	16.30-16.58	82.78-84.17	0.28-0.28
	Fuel oil	0.081-0.083	51.61-48.99	168.26-159.73	0.21-0.18
	Coal	0.048-0.056	23.28-23.26	237.40-237.29	0.26-0.26
HDD = 3750 °C days	Natural gas	0.043-0.054	16.88-17.16	85.73-87.14	0.27-0.27
	Fuel oil	0.082-0.086	53.44-50.73	174.25-165.41	0.21-0.17
	Coal	0.050-0.057	24.10-24.09	245.85-245.70	0.25-0.25
HDD = 4250 °C days	Natural gas	0.046-0.054	17.37-17.66	88.20-89.67	0.26-0.27
	Fuel oil	0.085-0.087	54.98-52.20	179.26-170.18	0.20-0.17
	Coal	0.050-0.060	24.80-24.78	252.92-252.77	0.24-0.24

Table A4. Optimum insulation thickness, energy savings and payback periods change ranges of the supply and return pipes (Ø150 mm) for 4th generation.

		Supply and return pipes (Ø150 mm)			
		4th generation			
		Optimum thickness m	Energy savings \$/m.year	Emission reduction kg CO_2/year	Payback period years
		RW-GW	RW-GW	RW-GW	RW-GW
HDD = 1250 °C days	Natural gas	0.030-0.035	11.65-11.68	42.51-39.59	0.38-0.36
	Fuel oil	0.055-0.062	32.05-31.68	84.48-84.44	0.23-0.23
	Coal	0.037-0.039	16.04-15.43	126.35-118.26	0.36-0.31
HDD = 2250 °C days	Natural gas	0.033-0.037	12.34-12.38	45.04-47.22	0.36-0.38
	Fuel oil	0.060-0.067	33.95-33.56	94.77-89.45	0.26-0.22
	Coal	0.037-0.040	16.99-16.94	133.82-125.29	0.34-0.29
HDD = 2750 °C days	Natural gas	0.035-0.040	13.06-13.10	47.68-49.98	0.34-0.36
	Fuel oil	0.063-0.072	35.93-35.52	100.29-94.65	0.24-0.20
	Coal	0.038-0.042	17.98-17.93	141.61-132.58	0.33-0.28
HDD = 3750 °C days	Natural gas	0.036-0.043	13.78-13.82	50.28-52.74	0.35-0.34
	Fuel oil	0.065-0.076	37.91-37.46	105.81-99.86	0.23-0.19
	Coal	0.039-0.045	18.97-18.92	149.41-151.88	0.31-0.32
HDD = 4250 °C days	Natural gas	0.038-0.048	14.38-14.43	52.50-55.03	0.31-0.33
	Fuel oil	0.068-0.080	40.43-39.12	110.42-113.44	0.22-0.25
	Coal	0.040-0.050	19.80-19.74	155.97-158.56	0.29-0.30

Nomenclature

C_f	Fuel cost, \$/m^3
C_{fl}	Annual fuel consumption cost occurred heat losses from pipes, \$/year
C_i	Cost of Insulation material per unit volume, \$/m^3
C_{ins}	Insulation cost, \$
C_m	Maintenance and operation cost, \$
C_{tot}	Total cost, \$
d	Inflation rate,%
D_t	Diameter of insulation pipe, m
E_s	Energy savings, \$/m
ES_{CO2}	Emission savins of CO_2, kg CO_2/year
EF	Emission factor of CO_2, kg CO_2/kWh
h	Heat convection coefficient, W/m^2.K
H_u	Lower heating value of the fuel, kJ/m^3
i	Interest rate,%
I_T	Total irreversibility
k	Thermal conductivity coefficient, W/m.K
L	Length, m
N	Lifetime, years

N_u	Nusselt number
Pr	Prandtl number
r_v	Ratio of resale value to first cost
R	Thermal resistance, $m^2.K/W$
Ra	Rayleigh number
Q	Heat transfer rate, kJ/s
Q_f	Annual fuel energy consumed from the heating system, kJ/year
t_c	Canal thickness, m
T	Temperature, °C
Tb	Base temperature, °C
T_{sa}	Solar-air temperature, °C
ύ	Volumetric flow rate, m^3/s
V	Volume, m^3
V_f	Annual fuel consumption of heating system, m^3/year
V_{pl}	Annual fuel consumption occurred heat losses from pipes, m^3/year
x_{cp}	Perimeter of canal, m
x_c	Dept of canal,m

Greek symbols

η_s	Efficiency of heating system, %

Subscripts

a	Air
i, ins	Insulation
un-ins	Uninsulation
c	Canal
C	Cost
D	Diameter
f	Fuel
fg	Flue gas
HDD	Heating degree-days
LCCA	Life cycle cost analysis
p	Pipe
pl	Loss from pipe
r_1	Inner radius
r_2	Outer radius
s	Soil
T_{sa}	Solar-air temperature
w	Water